Measurement of low frequency biomagnetic signals under non-periodical extramural noise by continuously adjusted least squares method

Y. Adachi[1], M. Shimogawara[1], M. Higuchi[1], Y. Haruta[2], and M. Ochiai[3]

[1]Applied Electronics Laboratory, Kanazawa Institute of Technology, Ishikawa, Japan;
[2]Yokogawa Electric Corp., Tokyo, Japan; [3]School of Medicine, Keio University, Tokyo, Japan

1 Introduction

One of the major concern during magneto-encephalograph (MEG) measurement in urban areas is the non-periodical low-frequency extramural magnetic noise which is mainly caused by transportation such as railroads and which is too large to attenuate sufficiently by a magnetically shielded room (MSR) at moderate price.

The bandwidth of the noise overlaps the slow components of biomagnetic responses such as motor related cortical fields (MRCF). Thus the generic high pass filter can't be applied to measure the low frequencies. Therefore MEG users often need a massive MSR with higher in order to measure such low-frequency MEG signals especially in urban areas.

We developed a signal processing method for noise reduction named CALM; Continuously Adjusted Least squares Method to improve the S/N ratio at less than 1 Hz enough to measure the low frequency MEG signals.

The outputs of sensors to observe the slow environmental magnetic variation are used as reference signals. They are weighted and then are subtracted from signals of MEG sensors. The weight of each reference signal in CALM can temporally change to be adapted for the unstable noise. They can effectively remove the non-periodical noise especially in cases where the sources of the noise, such as trains or cars, are multiple and the locations of the sources are moving independently.

In this paper, we reported what CALM was and discussed about its effectiveness in actual MEG measurement.

2 Methods

$x_i(t)$, which is the output from the *i* th MEG sensor, includes both $s_i(t)$, the objective MEG signal, and the environmental noise. The noise in $x_i(t)$ can be represented approximately by a linear sum of the noise measured exclusively by a number of *k* of reference magnetometers that are allocated away from the MEG sensors. Provided that each component of the environmental magnetic noise has long enough wave length, the objective signal can be represented as

$$s_i(t) = x_i(t) - \mathbf{w}_i(t) \cdot \mathbf{n}(t), \qquad (1)$$

where $\mathbf{n}(t)=(n_1(t), n_2(t), \ldots, n_k(t))$ is the set of data of the environmental noise measured by the reference sensors at time *t* and where $\mathbf{w}_i(t) =(w_{1i}(t), w_{2i}(t), \ldots, w_{ki}(t))$ is the set of weight coefficients for each reference signal related to the data of the *i* th MEG sensor.

The power of the signals after subtracting the approximated noise components should be a minimum. Therefore, the weights $\mathbf{w}_i(t)$ will be calculated so as to obtain the minimum *L* represented as the following:

$$L = \int_{t-T_1}^{t+T_2} \left(x_i(\tau) - \mathbf{w}_i(\tau) \cdot \mathbf{n}(\tau) \right)^2 d\tau. \qquad (2)$$

$[T_1, T_2]$ is the interval for calculating the weights. CALM outputs at time *t*, which is the noise-reduced signals, can be obtained by eq. (1) with the calculated weights $\mathbf{w}_i(t)$. The calculation of the weights is executed on each sampled data through the whole data sequence one by one. Therefore if the characteristic of the noise changes because of the transition of the noise source, CALM can remove the noise effectively by changing the weights adaptively.

3 MEG Measurements

Generally, when we apply a digital signal processing on an acquired data, we always have to care about whether the numerical operation has wrong effect on the true signals or not. We had four measurements to investigate how effectively CALM could reduce the environmental noise without distortion of the biomagnetic signals.

We installed 3-axis vector SQUID magnetometers to observe the environmental magnetic noise as reference sensors inside the dewar of the 150 ch

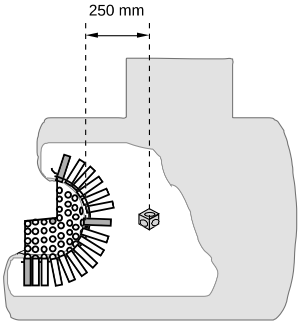

Figure 1: *The location of the set of reference sensors in the horizontal dewar. The shaded sensors of the array of the MEG sensors are the selected sensors in fig. 2*(*a*)*.*

whole cortex MEG system [1][2] in addition to the array of the MEG sensors. The location of the set of reference magnetometers was 250 mm away from the top of the array of the sensors as shown in fig.1. Both the MEG signals and the environmental noise were sampled simultaneously in each measurement at 500 Hz of sampling rate with DC – 200 Hz of bandwidth. After the whole data was acquired, CALM was applied to the data in the post acquisition processing. All MEG measurements were executed in the daytime in a standard MSR with two layers of mu-metal, located nearby the busiest railway in Tokyo, which had about 50 – 70 passages of trains an hour. The interval for calculating the weights in CALM was ten seconds derived by the heuristic method.

3.1 Measurement of alpha wave

A subject laid on the bed for MEG measurement and kept quiet with his eyes closed in order to measure his biomagnetic signals corresponding to alpha wave at first. The data for 500 sec were acquired. The time series of waveforms before and after applying CALM are shown in fig. 2(a) and both of the spectra are shown in fig. 2(b). Before applying CALM, the amplitude of the MEG signal sometimes exceeded over 50 pT_{pp} because of the non-periodical low-frequency noise. It is obvious that CALM reduced the noise drastically as shown in fig. 2(a). The noise under 1 Hz was reduced to 1/20 according to fig. 2(b). The peaks of the spectrum at about 10 Hz in correspond to alpha wave. Those two peaks were overlapped. It shows that CALM does not reduce the component of alpha wave.

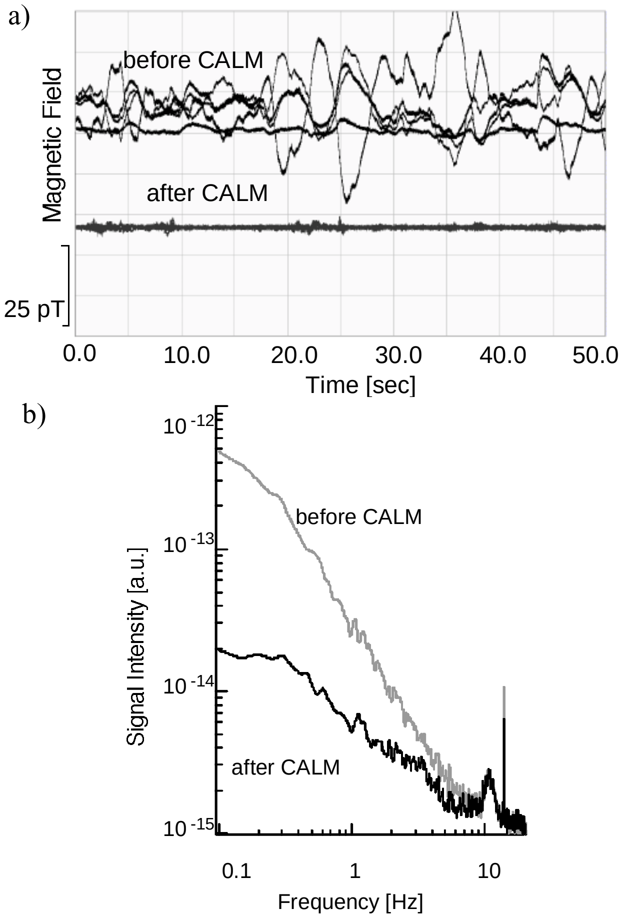

Figure 2: (a) *Comparison between the temporal waveforms of MEG signals in alpha wave recording. Each displayed data is from five sensors allocated over occipital, parietal, frontal and both temporal areas respectively.* (b) *The spectra of the data from a sensor allocated over the occipital area before and after applying CALM.*

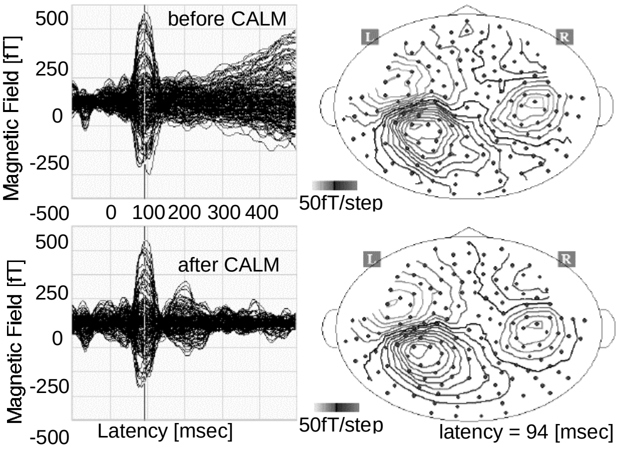

Figure 3: *Comparison of the waveforms of averaged data and the isofield contour maps at the latency of 94 msec between before and after applying CALM.*

3.2 Measurement of auditory evoked fields

The low-frequency noise does not matter in case of the measurement of auditory evoked fields (AEF) because their bandwidths don’t overlap. High pass filter (HPF) with 1 or 3 Hz of cut-off frequency can be applied to omit the low-frequency noise. We measured the AEF without HPF and compared the results before and after applying CALM in order to investigate the efficiency of CALM on measurement of the evoked fields.

Auditory stimulus was a tone of 1000 Hz whose duration was 50 msec, delivered through a plastic tube. Repeated stimuli were presented to a subject’s right ear. The inter-stimulus interval was 1 sec. CALM was applied to over all raw data including about 200 epochs. After and before applying CALM, all epochs were averaged respectively for improvement of signal noise ratio of the evoked response.

Figure 3 shows the time domain waveforms of AEF and isofield contour maps at the latency corresponding to N100.

It is obvious that CALM reduced the shifting of baselines of signals and made them stable. On the other hand, the signal of N100 weren’t affected by applying CALM because the intensity of the peak of N100 didn't differ between the data before and after applying CALM. The isofield contour map after applying CALM wasn’t distorted. The dipole-like pattern over temporal area of both hemispheres became clearer than of that before applying CALM.

3.3 Measurement of motor related cortical field

The MEG signals of subjects moving their fingers were recorded. Every subject was right-handed. They were tasked to move their right index fingers every five seconds. An optical switch monitored the movements of the finger. The output from the switch was recorded as triggering signal simultaneously with the MEG signals. Approximately one hundred motions were executed for five hundred seconds.

CALM was applied over all raw data and then the epochs synchronizing with the triggering signals were averaged to reduce the brain noise independent of the finger motion.

The time series waveforms of the averaged data acquired from the sensors allocated over the parietal area of the left hemisphere of one of the subjects are shown in fig. 4(a). The latency of 0 msec is the onset of the motion. The readiness field (RF), which is the slow shift of baselines that began one second before, was seen. The motor field (MF) and motor evoked field (MEF) can also be discriminated in the waveform [3]. Figure 4(b) shows the isofield contour map at the latency corresponding to the motor field. We can see the dipole-like pattern over the motor area of the left hemisphere. The equivalent current dipole of the source of the magnetic field was calculated from the data set of the motor field. It was superimposed on the MR image in Fig. 4(c). The position of the dipole was estimated at the precentral gyrus of the left hemisphere.

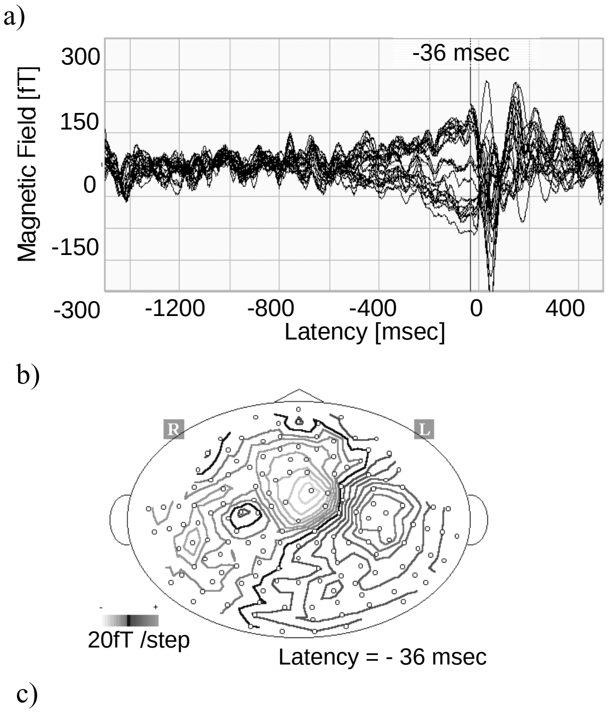

Figure 4: (a) *The time series waveforms of the averaged data of the MRCF measurement.* (b) *The isofield contour map at –36 msec of the latency.* (c) *The equivalent current dipole estimated from the data at –36 msec, which is superimposed on MR image.*

3.4 Measurement of event-related field

We measured the MEG signals under the auditory oddball paradigm [4]. Subjects were presented two types of auditory stimuli: frequent tone (1000Hz) and rare tone (2000Hz). The stimulus sequence consisted of 80 % frequent tone and 20 % rare tone. The duration of both tones was 100 msec. The

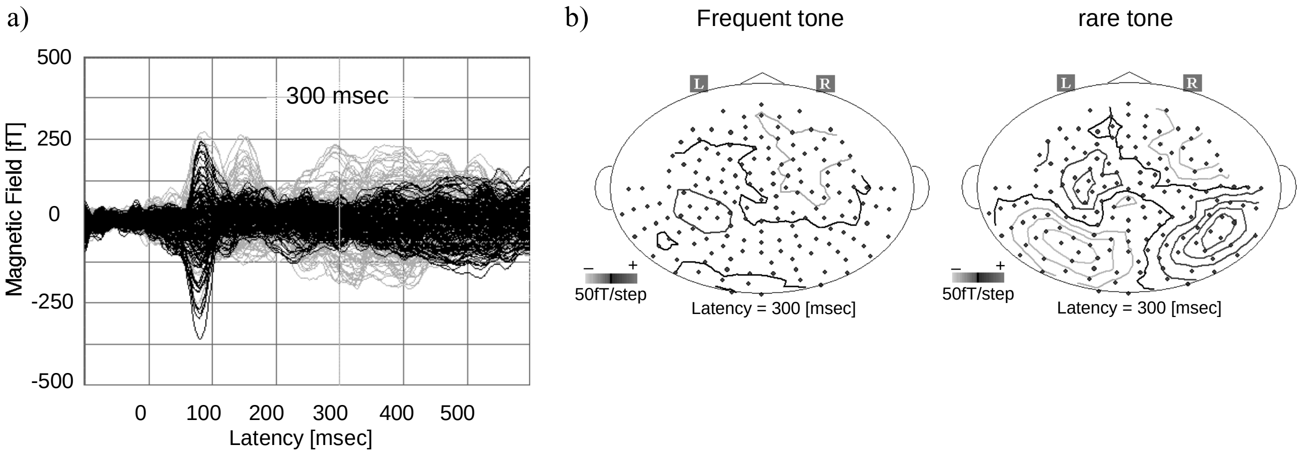

Figure 5: (a) *Comparison between the waveforms of the response to the frequent tone* (*black lines*) *and the rare tone* (*gray lines*)*. Both are the averaged data of 30 epochs. The MEG signals from all 150 sensors are overlapped.* (b) *The isofield contour maps at 300 msec of the latency. The left and right maps are corresponding to the responses to the frequent and rare tones, respectively.*

interval of stimulus was 2 sec. The tones were delivered binaurally through plastic tube. Subjects were tasked to count mentally the number of the rare stimulus. The length of the recorded MEG signals was about 300 sec and, consequently, they contained at least 30 epochs for the rare stimulus. The time series of the responses of the one of the subjects to both stimuli was shown in fig. 5(a). Figure 5(b) shows the isofield contour map at 300 msec of the latency. In the response to the rare tone, some broad peaks in addition to the N100 component were observed.

4 Discussion

The correlation coefficient between $x_i(t)$ and $\mathbf{w}_i(t)\cdot\mathbf{n}(t)$ in eq. (2) should be largest with the set of the calculated weights. In other words, CALM subtracts the components that have the large correlation between the signal of the MEG sensor and reference signals. Therefore the biomagnetic signals aren't suffering from applying CALM. The extramural low-frequency noise have long wavelength and then they are included in outputs from both the MEG sensor and the reference sensors, while the biomagnetic signals are only contained in the signals from the MEG sensors.

The former two MEG measurements showed that CALM reduced only environmental noise but didn't damage the biomagnetic signals. Furthermore, the result of the measurement of MRCF appears to be appropriate according to the location of the dipole in fig. 4(c).

It shows that CALM is an efficient enough method of noise reduction for the measurement of low-frequency component of MEG signals under the severe environmental magnetic noise. CALM will promote further the study of the MEG measurements in urban area such as Tokyo.

Acknowledgments

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Reference

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